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RESEARCH MEMORANDUM

COMBUSTION-EFFICIENCY INVESTIGATION OF SPECIAL FUELS IN SINGLE TUBULAR-TYPE COMBUSTOR AT SIMULATED ALTITUDE CONDITIONS

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RESEARCH MEMORANDUM

COMBUSTION-EFFICIENCY INVESTIGATION OF SPECIAL FUELS IN SINGLE TUBULAR-TYPE COMBUSTOR AT SIMULATED ALTITUDE CONDITIONS

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SUMMARY

A combustion-efficiency investigation of 10 special straight-run distillate fuels was conducted in an individual tubular-type combustor unit of a 14-unit assembly at two simulated engine operating conditions. These distillates were obtained from various crude oils and consisted of hydrocarbon mixtures with distillation temperature varying from 93° to 690° F. Three commercial fuels were also tested, one of which was used for checking reproducibility. The operating conditions simulated engine operation at an altitude of 40,000 feet at engine speeds of 7000 and 10,500 rpm.

Comparison of temperature measurements obtained from two locations in the exhaust duct showed that under certain operating conditions the flame extended beyond the turbine position.

The data obtained in these fuel tests showed that as the distillation temperature of the fractions from the same crude increased, the combustion efficiency decreased. Correlations are shown of combustion efficiency with the 50-percent boiling point, with viscosity, and with an empirical function of the 50-percent boiling point and specific gravity.

INTRODUCTION

At the request of the NACA Subcommittee on Aircraft Fuels and Lubricants, the Bureau of Mines conducted a survey of the possible crude-oil sources for jet-propulsion engine fuels and determined the chemical and physical properties of many straight-run distillates at the Petroleum Experiment Station, Bartlesville, Oklahoma. As part of this program, the NACA Cleveland laboratory was requested to investigate the combustion efficiencies of such fuels.

For this purpose 10 straight-run distillates were obtained from five crude-oil sources. These special fuels together with three commercial fuels were tested in a single tubular-type combustor. The experimental conditions were chosen on the basis of previous data (reference 1), which indicate that for a given altitude the combustion efficiency decreases with a decrease in engine speed. Conditions simulating engine operation at an altitude of 40,000 feet at engine speeds of 7000 and 10,500 rpm were considered to be sufficiently severe to reveal any differences that might exist in the combustion of the various fuels.

An investigation was also made to determine the effect that thermocouple location in the exhaust duct would have on the test results. One of the commercial fuels was run either before or after each test fuel to determine the reproducibility of the test results. The results of these investigations and possible correlations of fuel performance with fuel properties are presented.

FUELS

The chemical and physical properties of the straight-run distillates as determined by the Bureau of Mines are shown in table I. The properties of the commercial fuels were determined by the NACA (table II).

The 10 special straight-run distillates were obtained from five crude oils. The sources of the crude oils and the distillation temperatures were selected to provide a wide variety of physical properties and hydrocarbon types. These fuels were mixtures of hydrocarbon types in which paraffins ranged from 0 to 74.02 percent (by volume), naphthenes ranged from 18.50 to 78.02 percent, monocyclic aromatics from 5.33 to 33.03 percent, and dicyclic aromatics from 0 to 11.50 percent. The A.S.T.M. distillation temperatures of these fuels varied over a range between 93° and 690° F.

Of the commercial fuels, solvent 1 was used to determine the reproducibility of combustor performance; whereas AN-F-32 and Diesel oil (Fischer-Tropsch process) were run only for comparison.

APPARATUS AND PROCEDURE

A single combustor of an I-40 jet-propulsion engine and the test setup described in reference 2 were used in this investigation with several minor modifications (fig. 1).

During preliminary trials, a temperature survey of the gases in the outlet duct at the turbine position showed the maximum temperatures to be near a segment of the duct wall, thus indicating faulty air distribution. Examination of the combustor assembly revealed that the air-passage annulus between the dome and the liner was nonuniform. Nine spacers were attached to the outer rim of the combustor dome to provide an annulus of uniform width (section A-A, fig. 1). This change improved the symmetry of the temperature pattern in the outlet duct.

Thermocouples for the measurement of combustor-outlet temperatures were located at two stations (fig. 1). Station 1 was equivalent to the turbine position in the engine assembly and station 2 was located 45 inches downstream of station 1. At station 1, 16 chromel-alumel thermocouples were equally spaced along the center lines of two equal areas. A similar arrangement with 12 thermocouples along the center lines of three equal areas was used at station 2.

The fuel flow was measured by a rotameter that was calibrated for each fuel. A standard I-40, 40-gallon-per-hour, 80° spray-angle fuel nozzle was used throughout this investigation.

The test conditions simulated operation of an I-40 jet-propulsion engine at an altitude of 40,000 feet at engine speeds of 7000 and 10,500 rpm. The specific inlet-air conditions are given in the following table:

Simulated operation		Combustor-inlet air			
Altitude (ft)	Engine speed (rpm)	Mass flow[a] (lb/sec)	Velocity[b] (ft/sec)	Pressure (in. Hg abs.)	Temperature (°F)
40,000	10,500	1.00	129	20.5	235
40,000	7,000	.62	118	11.0	90

[a]Per combustor.
[b]At 6-in.-diam. cross section.

For each fuel run, a set of inlet-air conditions was held constant while the fuel flow was varied to give a series of points in which the temperature rise through the combustor ranged from 500° to approximately 1500° F. For each data point, the fuel flow and the temperature measurements at both stations were recorded.

The commercial fuel that was used for checking the reproducibility of combustor performance was tested either before or after each fuel run. A comparison of the results from the two thermocouple stations for Tomball 1B fuel is shown in figure 2.

At the simulated 10,500 rpm condition, the agreement in efficiency values from these two stations indicates that no appreciable combustion takes place between them. Although combustion is not complete at station 1, as shown by the efficiency values, no appreciable burning occurs downstream. At the simulated 7000 rpm condition, the efficiency values from the two stations are comparable at heat-input values less than approximately 360 Btu per pound of air; but as the heat input is increased above this value, the efficiency at station 2 increases at a greater rate than at station 1. That is, when the combustion efficiency at station 1 is low for a high heat input, considerable afterburning may be expected. This afterburning was observed through a window that was located 4 inches downstream of station 1. Similar results were obtained with the other fuels but the maximum difference in efficiency between stations 1 and 2 decreased as the volatility of the fuel increased.

Temperature measurements from station 1 were used in computing the combustion-efficiency values, inasmuch as engine operation is dependent upon the temperature rise of the gases previous to their flow through the turbine.

RESULTS AND DISCUSSION

The reproducibility of the data as determined by the results of the repeated runs with solvent 1 is shown in figure 3. The series of points indicate typical check runs and the dashed lines indicate the band within which all data of the check runs were plotted.

In figure 4(a) to (e), in which percentage combustion efficiency is plotted against heat input in Btu per pound of air, are shown the experimental results obtained with the 10 straight-run distillates at the two operating conditions. These results are grouped according to the crude-oil sources of the distillates. Combustion efficiency was calculated as the ratio of actual temperature rise to the theoretical temperature rise. Heat input in Btu per pound of air is the product of fuel-air ratio times the lower heating value of the fuel. The dashed lines are required combustor-temperature-rise lines. NACA data show that a temperature rise of 892° F is required for engine operation at 7000 rpm, and 971° F is required for 10,500 rpm at an altitude of 40,000 feet. At these required temperature-rise lines the heat input and the resulting combustion efficiency are shown for each fuel at the two simulated engine speeds.

The comparison of the performance of the distillates from any one crude shows that for a given heat input the combustion efficiency of the low-boiling fuel is greater than the efficiency of the high-boiling fuel and that this difference is greater at the simulated 7000 rpm condition. These figures also show that any one fuel, at a given heat input, gives a higher combustion efficiency at the simulated 10,500 rpm condition than at the simulated 7000 rpm condition and that this change in efficiency is more pronounced for the higher boiling fuels.

The performance of AN-F-32 and Diesel oil at the same experimental conditions is shown in figure 4(f). The correlation between the combustion-efficiency values at the required combustor temperature rise (fig. 4) and the 50-percent boiling point of the fuels is shown in figure 5. This correlation indicates a gradual decrease in fuel performance with increasing 50-percent boiling point up to approximately 500° F, after which the decrease in efficiency is more pronounced. No explanation is evident for the behavior of Bradford 2A fuel at the simulated engine speed of 7000 rpm.

In figure 6, these efficiency values are plotted against the viscosity of the fuel. This correlation is similar to figure 5 as was expected because of the relation that exists between boiling point and viscosity for most hydrocarbon types.

An empirical function of the 50-percent boiling point and specific gravity of the fuels is plotted against combustion efficiency at the two simulated engine speeds in figure 7. The reciprocal of the 50-percent boiling point was taken as a measure of volatility and specific gravity as a factor influenced by hydrocarbon composition. This empirical function was used in correlating flame stability during a preliminary investigation of jet-propulsion fuels by the Standard Oil Company of Indiana in 1946. This function consisted of the reciprocal of the logarithm of the 50-percent boiling point divided by the square root of the specific gravity:

$$\frac{1/\log \text{50-percent boiling point}}{\sqrt{\text{specific gravity}}}$$

From these correlations it is evident that the distillation temperature and related properties are a decisive factor in determining fuel performance at conditions approaching combustor operational limits. These results are in agreement with the general conclusions of reference 2, in which a preliminary investigation of fuel performance at altitude conditions is reported. The effect of chemical composition, which varied with the source of the crude oils, upon combustion efficiency was not evident, possibly due to the heterogeneous composition of the fuels.

In figure 8, the difference in percentage combustion efficiency for the two simulated engine speeds is plotted against the 50-percent boiling point of the various fuels. This figure shows that the difference in combustion efficiency with change in engine speed increased as the distillation temperatures of the fuels increased.

SUMMARY OF RESULTS

From a combustion-efficiency investigation of 10 straight-run distillates and three commercial fuels in a single tubular-type combustor at two simulated operating conditions, the following results were obtained:

1. For distillates from the same crude, the results showed that as the distillation temperature increased the combustion efficiency at the required temperature rise for engine operation decreased.

2. The combustion efficiencies of the various fuels were correlated with the 50-percent boiling point, with viscosity, and with an empirical function of the 50-percent boiling point and specific gravity.

3. No significant difference in combustion efficiency due to crude-oil source was detected in these fuel tests, that is, the correlations shown were independent of fuel source.

4. The difference in combustion efficiency with change in simulated engine speed increased as the distillation temperature of the fuels increased.

Flight Propulsion Research Laboratory,
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Cleveland, Ohio.

REFERENCES

1. Childs, J. Howard, McCafferty, Richard J., and Surine, Oakley W.: Effect of Combustor-Inlet Conditions on Performance of an Annular Turbojet Combustor. NACA TN No. 1357, 1947.

2. Tischler, Adelbert O., and Dittrich, Ralph T.: Fuel Investigation in a Tubular-Type Combustor of a Jet-Propulsion Engine at Simulated Altitude Conditions. NACA RM No. E7F12, 1947.

TABLE I - PHYSICAL AND CHEMICAL PROPERTIES OF

Property	Tomball 1A	Tomball 1B	Bradford 2A
Distillation temperature, °F			
A.S.T.M. method D 86-40			
Initial boiling point	199	357	93
Percent evaporated			
5	219	420	103
10	224	432	138
30	244	464	194
50	262	486	234
70	286	507	270
90	315	540	311
95	327	568	329
End point	338	584	372
Specific gravity, 60/60° F	0.7911	0.8513	0.7208
°A.P.I.[1]	47.4	34.7	64.8
Density 20° C	0.7852	0.8468	0.7146
Correlation index[1]	39	39	11
Flame height, millimeters	15	13	20
Refractive index			
n_D 20° C[2]	1.44063	1.47559	1.40269
n_g 20° C[3]	1.45336	1.49038	1.41181
n_e 20° C[4]	1.44311	1.47837	1.40466
Kinematic viscosity, centistokes:			
A.S.T.M. method D 445-42T			
100° F (37.8° C)	0.676	2.313	0.564
-40° F (-40° C)	2.153	Frozen	1.662
Aniline point, A.S.T.M. method D 611-41T			
°F	81.0	138.0	136.0
°C	27.0	59.0	58.0
Freezing point, °F	Below-76	-17	Below-76
Sulfur weight, percent	0.00	0.08	0.03
Bromine number, A.S.T.M. method ES-45a	0.06	3.36	0.21
Flash point, °F		180	
Molecular weight[1]	113	192	110
Molecular volume[1]	144	227	154
Aniline function[1]	85	122	95
Molecular refraction[1]	38	64	38
ΔDispersion[1]	127.3	147.9	91.2
Specific dispersion[1]	162.1	174.7	127.6
Refractivity intercept[1]	1.0480	1.0522	1.0454

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[1]Calculated values:

$°A.P.I. = \frac{141.5}{G}$ where G is specific gravity at 60/60° F.

Correlation index $= \frac{48,640}{K} + 473.7G - 456.8$ where

K is average boiling point in degrees Kelvin.

[2]n_D = refractive index for the sodium D line.

[3]n_g = refractive index for the mercury g line.

[4]n_e = refractive index for the mercury e line.

STRAIGHT-RUN DISTILLATES AS DETERMINED BY BUREAU OF MINES

Bradford 2B	Midway 3A	Midway 3B	Yates 4A	Hastings 5A	Hastings 5B	Hastings 5C
324	104	287	149	97	278	374
353	138	425	185	136	301	433
366	159	445	203	156	308	451
410	220	475	221	192	327	483
441	262	506	259	215	343	511
470	309	543	286	235	361	546
506	357	594	311	272	388	624
524	374	621	334	292	402	682
540	396	625	356	319	420	690
0.7983	0.7670	0.8794	0.7446	0.7396	0.8101	0.8606
45.7	53.0	29.4	58.5	59.8	43.2	32.9
0.7945	0.7652	0.8746	0.7408	0.7342	0.8060	0.8580
19	29	50	18	24	36	41
18	20	12	20	20	17	14
1.44387	1.42355	1.48375	1.41354	1.40888	1.44685	1.47525
1.45477	1.43362	1.49785	1.42324	1.41812	1.45830	1.48844
1.44599	1.42544	1.48645	1.41538	1.41062	1.44904	1.47782
1.701	0.702	3.218	0.641	0.595	1.051	3.408
Frozen	2.505	114.81	2.128	1.918	5.098	125.15
160.0	120.0	124.4	132.8	120.4	117.0	146.8
71.0	49.0	51.2	55.9	49.2	47.0	63.9
-29	Below-76	Below-76	Below-76	Below-76	Below-76	-63
0.14	0.05	0.45	0.03	0.00	0.03	0.13
6.63	0.30	6.65	Neg.	Neg.	Neg.	2.62
137		149			89	184
183	115	197	119	104	138	204
230	151	225	161	142	171	238
126	93	119	98	89	99	128
61	38	64	40	35	46	67
109.0	100.7	141.0	97.0	92.4	114.5	131.9
137.0	131.5	161.2	130.9	125.9	142.1	153.7
1.0466	1.0410	1.0465	1.0431	1.0418	1.0439	1.0463

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TABLE I - PHYSICAL AND CHEMICAL PROPERTIES OF STRAIGHT-RUN

Property	Tomball 1A	Tomball 1B	Bradford 2A
Hydrocarbon analysis, A.S.T.M. method ES-45a			
Extract (aromatic) volume, percent	35.7	29.9	10.9
Density 20° C[1]	0.8504	0.9428	0.7936
n_D 20° C[1]	1.48487	1.54585	1.45339
n_g 20° C[1]	1.50387	1.57197	1.46450
Monocyclic aromatics volume, percent[1]	100	100	100
Dicyclic aromatics volume, percent[1]	0	0	0
Raffinate volume, percent	64.3	70.1	89.1
Density 20° C	0.7490	0.8059	0.7049
n_D 20° C	1.41607	1.44562	1.39649
n_g 20° C	1.42532	1.45558	1.40537
Naphthene rings weight, percent[1]	32.6	29.8	0
Paraffin and paraffin side chains weight percent[1]	67.4	70.2	100
Silica gel hydrocarbon analysis			
Extract (aromatic) volume, percent	31.30	32.25	7.48
Density 20° C			
n_D 20° C			
n_g 20° C			
n_e 20° C			
Monocyclic aromatics volume, percent[1]	100	64.3	100
Dicyclic aromatics volume, percent[1]	0	35.7	0
Raffinate volume, percent	68.70	67.76	92.52
Density 20° C	0.7497	0.7930	0.7123
n_D 20° C	1.41632	1.44119	1.39975
n_g 20° C	1.42550	1.45091	1.40845
n_e 20° C	1.41801	1.44305	1.40147
Naphthene rings weight, percent[1]	33.1	19.7	5.8
Paraffin and paraffin side chains weight percent[1]	66.9	80.3	94.2
Estimated best analysis of total sample			
Paraffin volume, percent	30.90	31.85	74.02
Naphthenes volume, percent	37.80	35.90	18.50
Monocyclic aromatics volume, percent	31.30	20.75	7.48
Dicyclic aromatics volume, percent	0	11.50	0
Naphthene rings weight, percent	21.7	12.5	5.3
Paraffin and paraffin side chains weight, percent	43.9	51.0	86.9
Hydrogen-carbon ratio, weight[2]	0.143	.157	.181
Lower heating value, Btu/lb[2]	17,760	18,300	18,890

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[1]Calculated values.

[2]Analysis by NACA.

DISTILLATES AS DETERMINED BY BUREAU OF MINES - Concluded

Bradford 2B	Midway 3A	Midway 3B	Yates 4A	Hastings 5A	Hastings 5B	Hastings 5C
17.1	11.6	29.4	7.3	6.6	18.5	20.2
0.8532	0.8560	0.9422	0.8462	0.7924	0.8692	0.9257
1.48906	1.47534	1.53742	1.47986	1.44440	1.49630	1.53836
1.50573	1.49190	1.55993	1.49671	1.45924	1.51459	1.58198
100	100				100	60
0	0				0	40
82.9	88.4	70.6	92.7	93.4	81.5	79.8
0.7824	0.7533	0.8465	0.7326	0.7301	0.7916	0.8408
1.43455	1.41675	1.46140	1.40832	1.40637	1.43585	1.45928
1.44426	1.42597	1.47200	1.41745	1.41521	1.44552	1.46477
18.2	37.9	59.4	17.2	32.8	47.8	53.5
81.8	62.1	40.6	82.8	67.2	52.2	46.5
12.45	9.72	33.23	5.91	5.33	16.82	26.17
		0.9431			0.8799	0.9363
1.51573		1.53277			1.50524	1.53353
1.53639		1.55408			1.50904	1.55619
1.51950		1.53647			1.52551	1.53771
	100	99.4	100	100	88.7	90.9
	0	0.6	0	0	11.3	9.1
87.55	90.28	66.77	94.09	94.67	83.18	74.83
0.7788	0.7608	0.8405	0.7356	0.7389	0.7915	0.8311
1.43408	1.41998	1.45964	1.40971	1.40998	1.43677	1.45639
1.44359	1.42918	1.46980	1.41869	1.41899	1.44546	1.46664
1.43586	1.42167	1.46146	1.41134	1.41163	1.43761	1.45832
15.3	44.2	54.9	20.9	41.9	47.7	45.1
84.7	55.8	45.1	79.1	58.1	52.3	54.9
54.25	24.38	0	58.34	31.25	4.98	0
33.30	65.90	66.77	35.75	63.42	78.20	74.83
12.45	9.72	33.03	5.91	5.33	14.92	22.87
0	0	0.20	0	0	1.90	2.30
13.1	39.7	35.2	19.5	39.7	39.0	32.7
72.7	50.1	28.9	73.9	55.0	42.7	39.8
.169	.170	.147	.176	.172	.158	.154
18,650	18,630	18,170	18,800	18,800	18,570	18,400

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TABLE II - PHYSICAL AND CHEMICAL PROPERTIES
OF THREE COMMERCIAL FUELS AS DETERMINED BY NACA

Property	AN-F-32	Diesel oil (Fischer-Tropsch)	Solvent 1
Distillation temperature, °F, A.S.T.M. Method D 86-45			
Initial boiling point	314	376	307
Percent evaporated			
5	336	420	319
10	344	436	322
30	354	456	330
50	366	476	338
70	382	506	347
90	422	544	363
End point	480	592	382
Specific gravity, 60/60° F	0.791	0.776	0.769
°A.P.I.[1]	47.5	50.9	52.5
Aniline point, °F			157.3
Freezing point, °F	Below-76	21	Below-76
Bromine number		1.56	0.3
Flash point, °F	115	165	97
Hydrocarbon analysis, A.S.T.M. method ES-45a			
Extract (aromatic), volume percent	10.8	9.5	1.1
Hydrogen-carbon ratio, weight	0.172	0.181	0.174
Lower heating value, Btu/lb	18,700	18,900	18,800

[1] $^{\circ}\text{A.P.I.} = \dfrac{141.5}{\text{sp. gr. } 60/60^{\circ}\text{ F}} - 131.5.$

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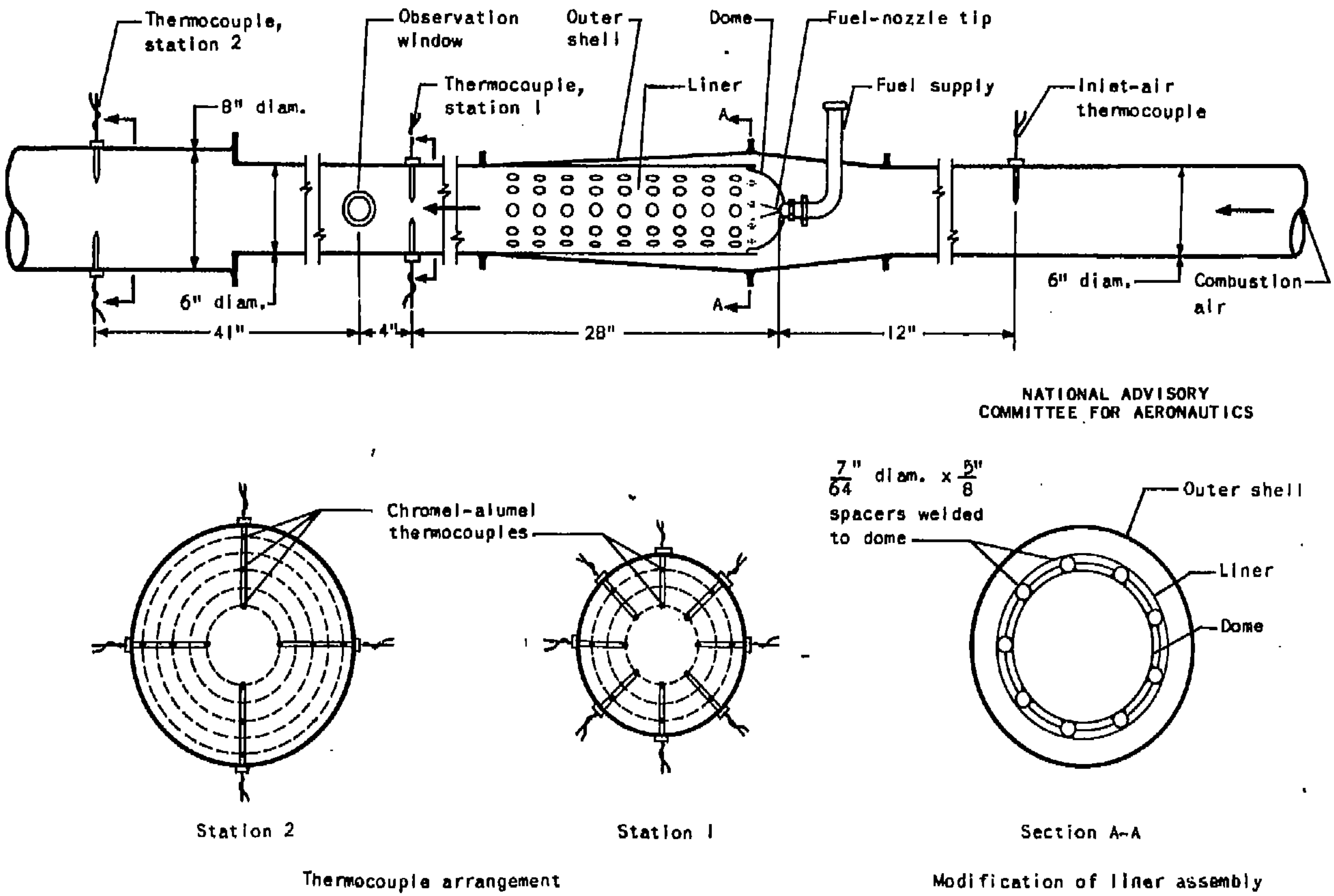


Figure 1. - Diagrammatic sketch of single tubular-type combustor showing modification of liner assembly and thermocouple locations.

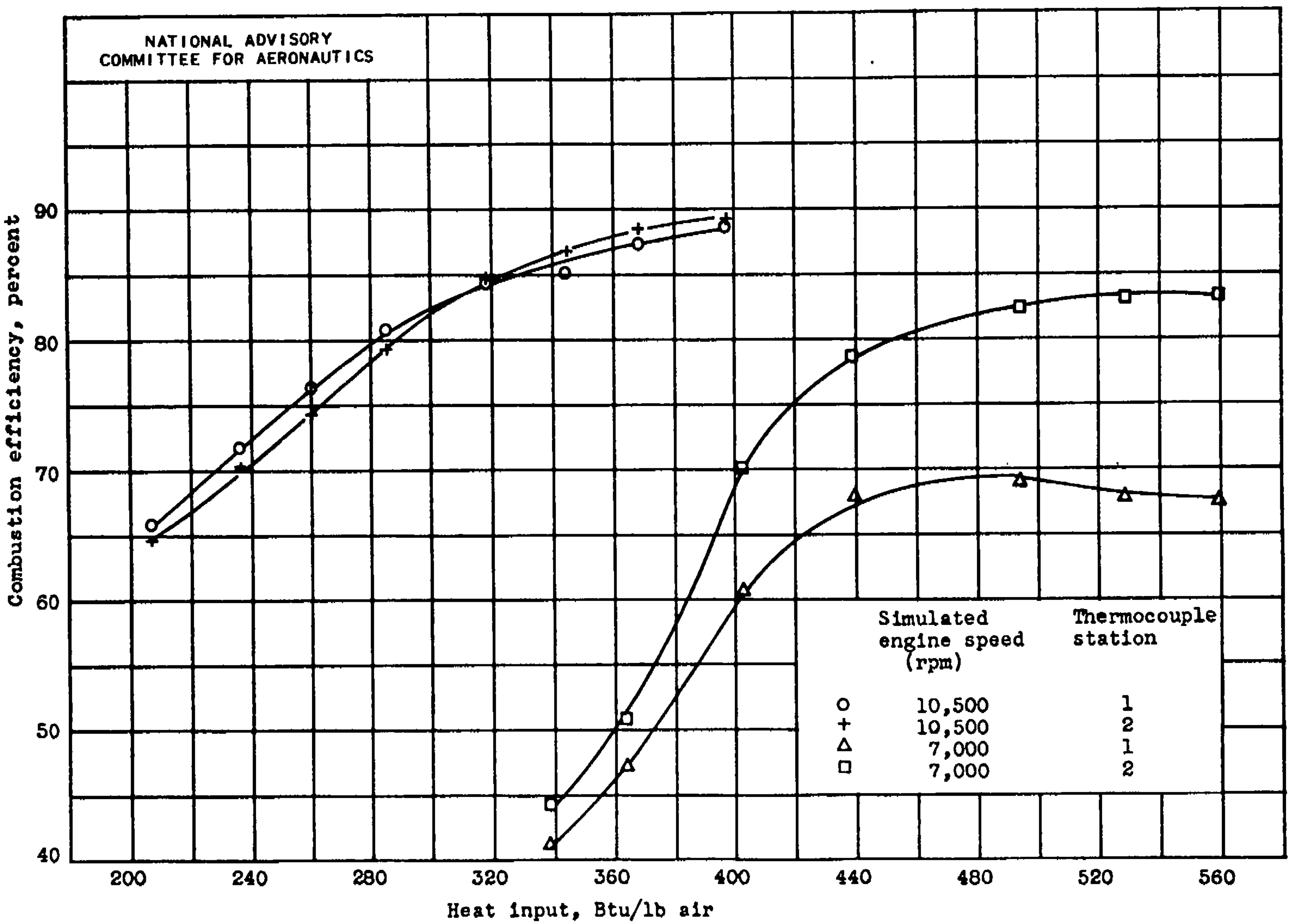


Figure 2. - Comparison of combustion-efficiency values from two thermocouple stations for Tomball 1B fuel. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.

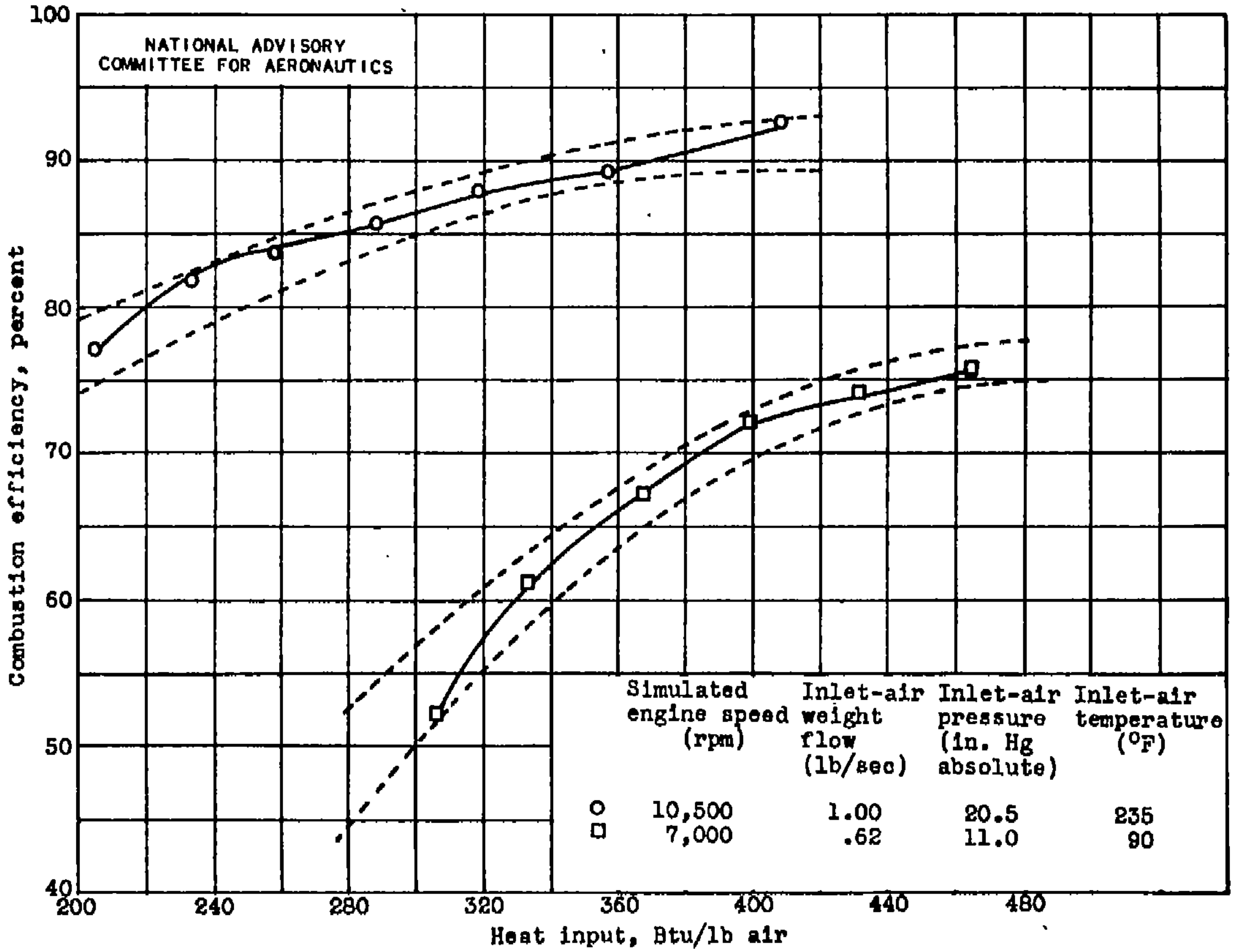
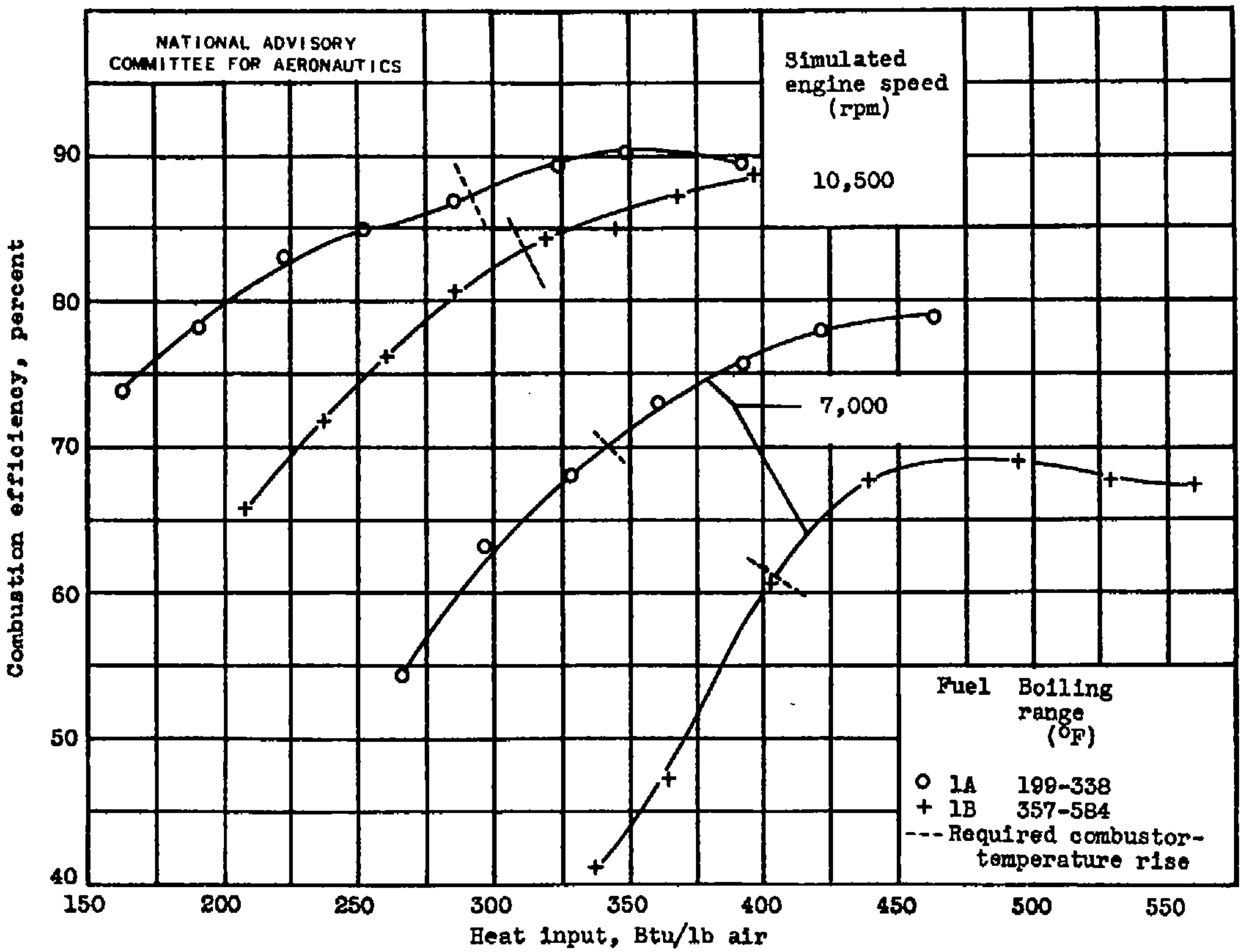
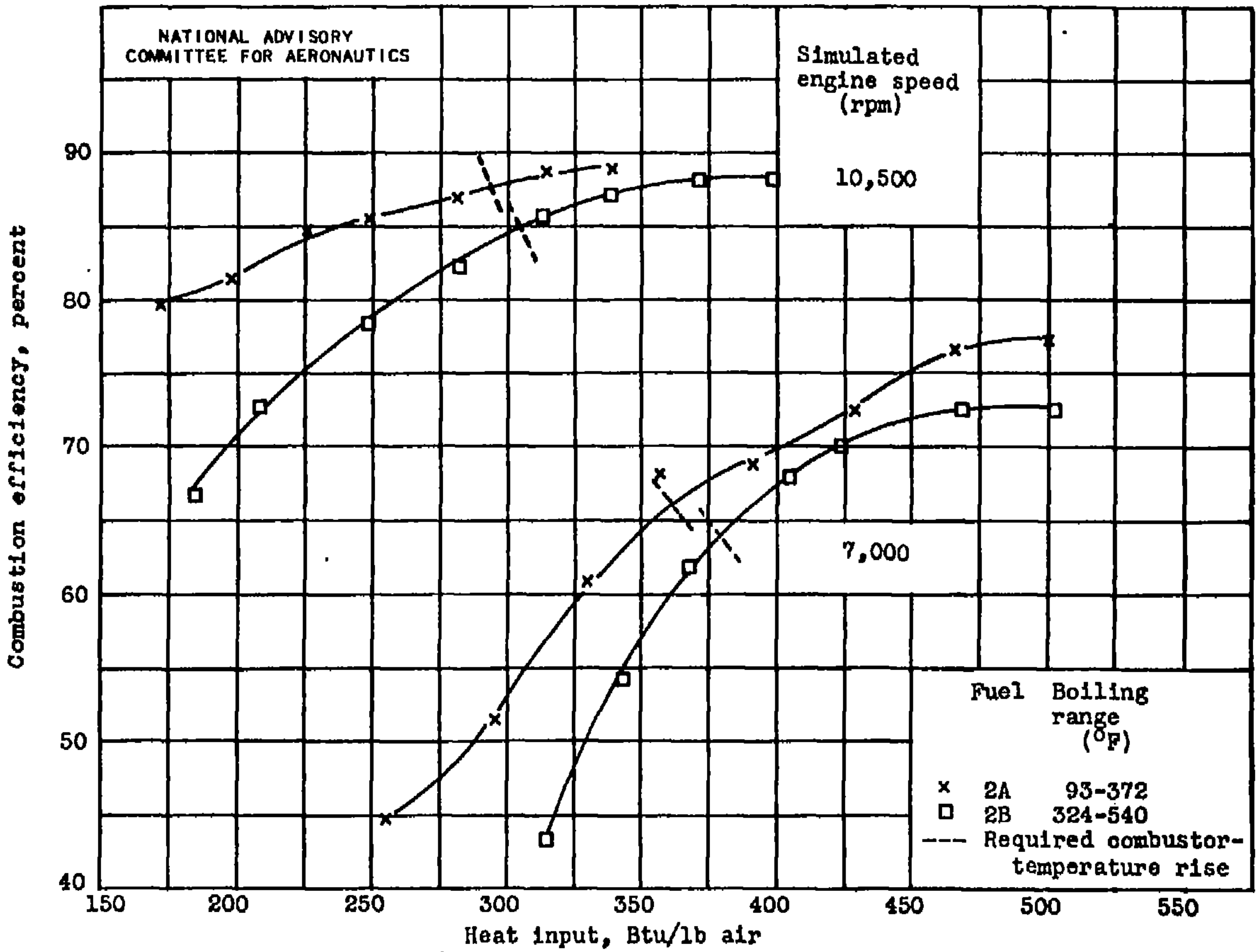


Figure 3. - Typical check runs with solvent 1 fuel. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds. (Each pair of dashed lines indicates limits within which all check-run data were plotted.)



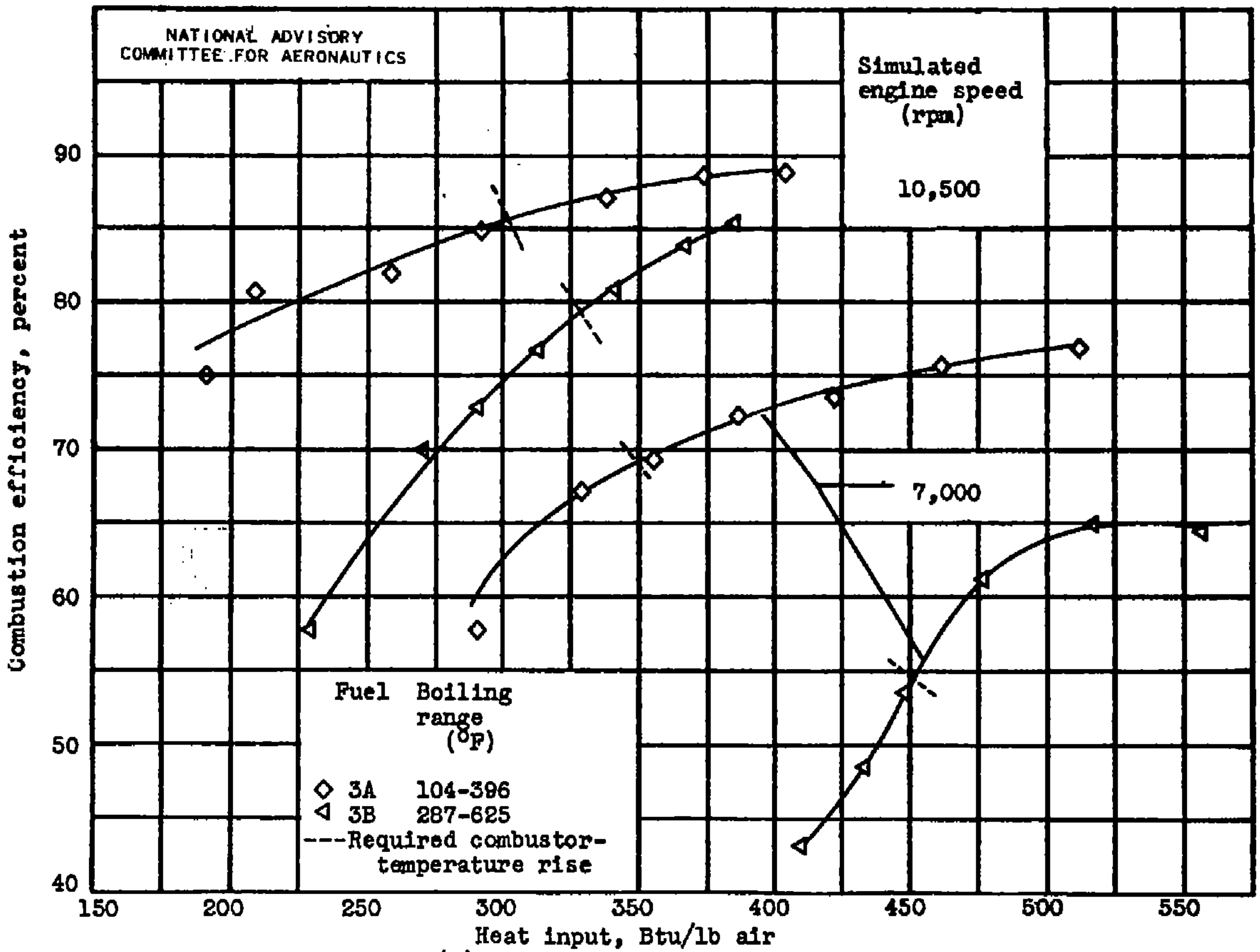
(a) Fuels: Tomball 1A and 1B.

Figure 4. - Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



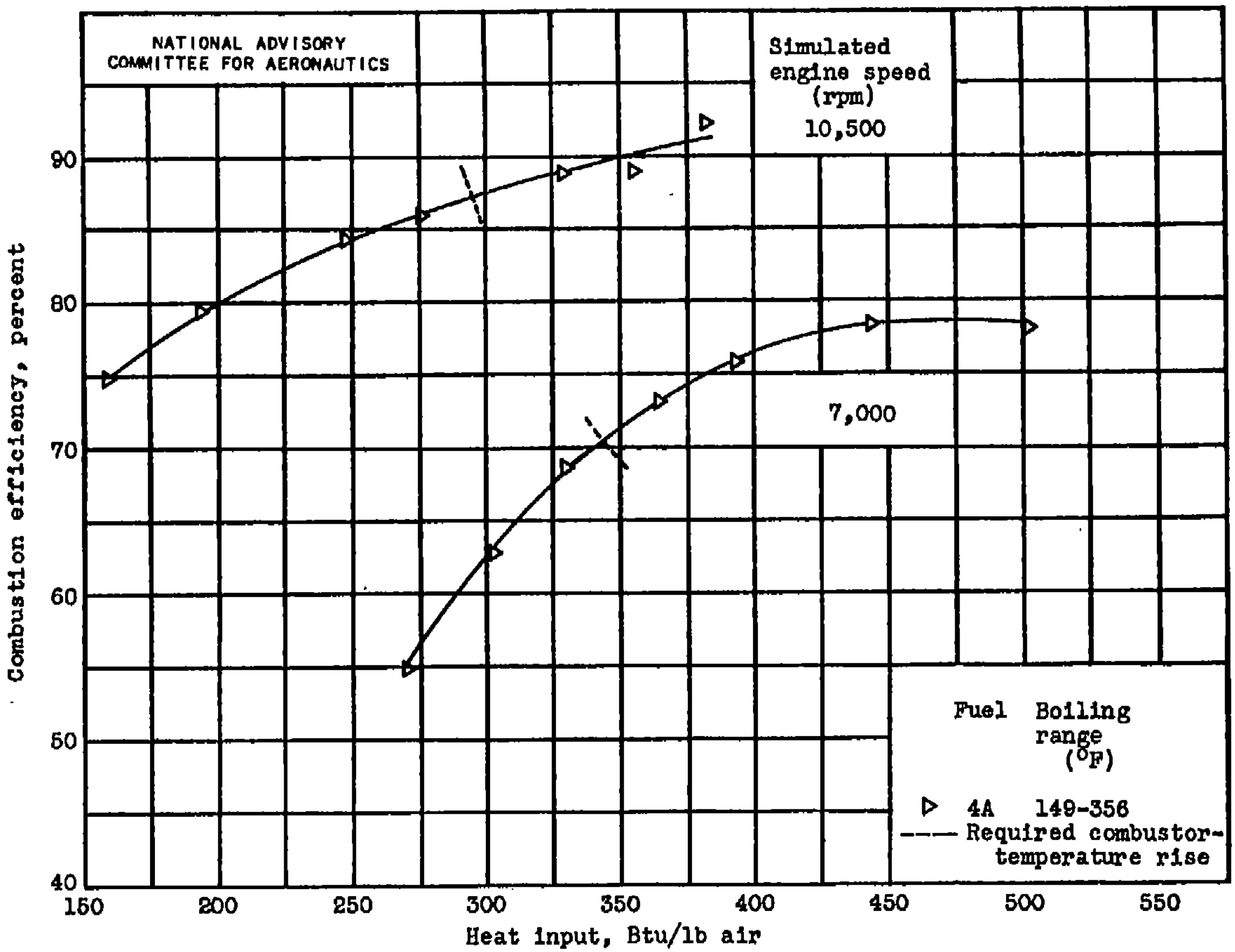
(b) Fuels: Bradford 2A and 2B.

Figure 4. - Continued. Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



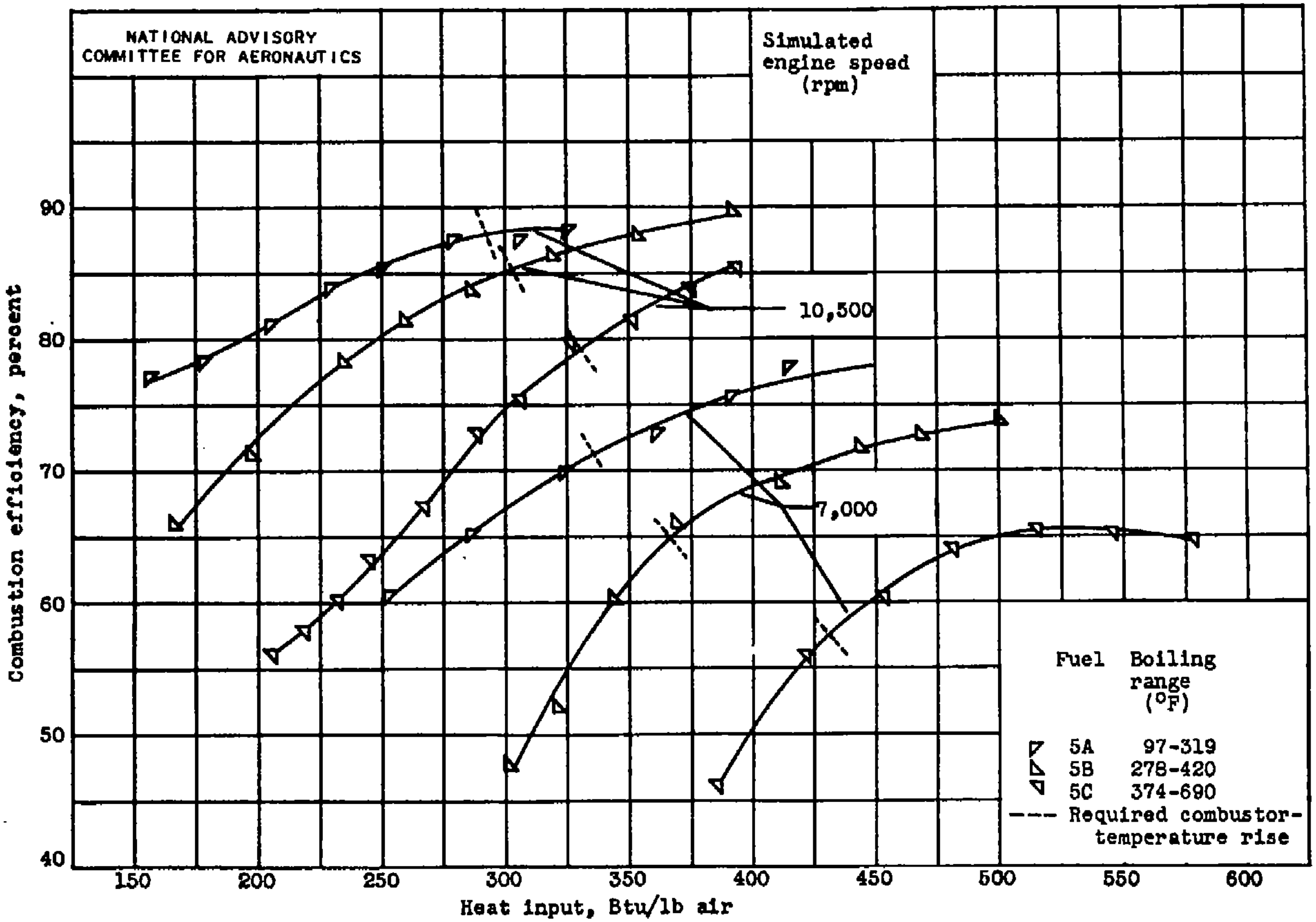
(c) Fuels: Midway 3A and 3B.

Figure 4. - Continued. Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



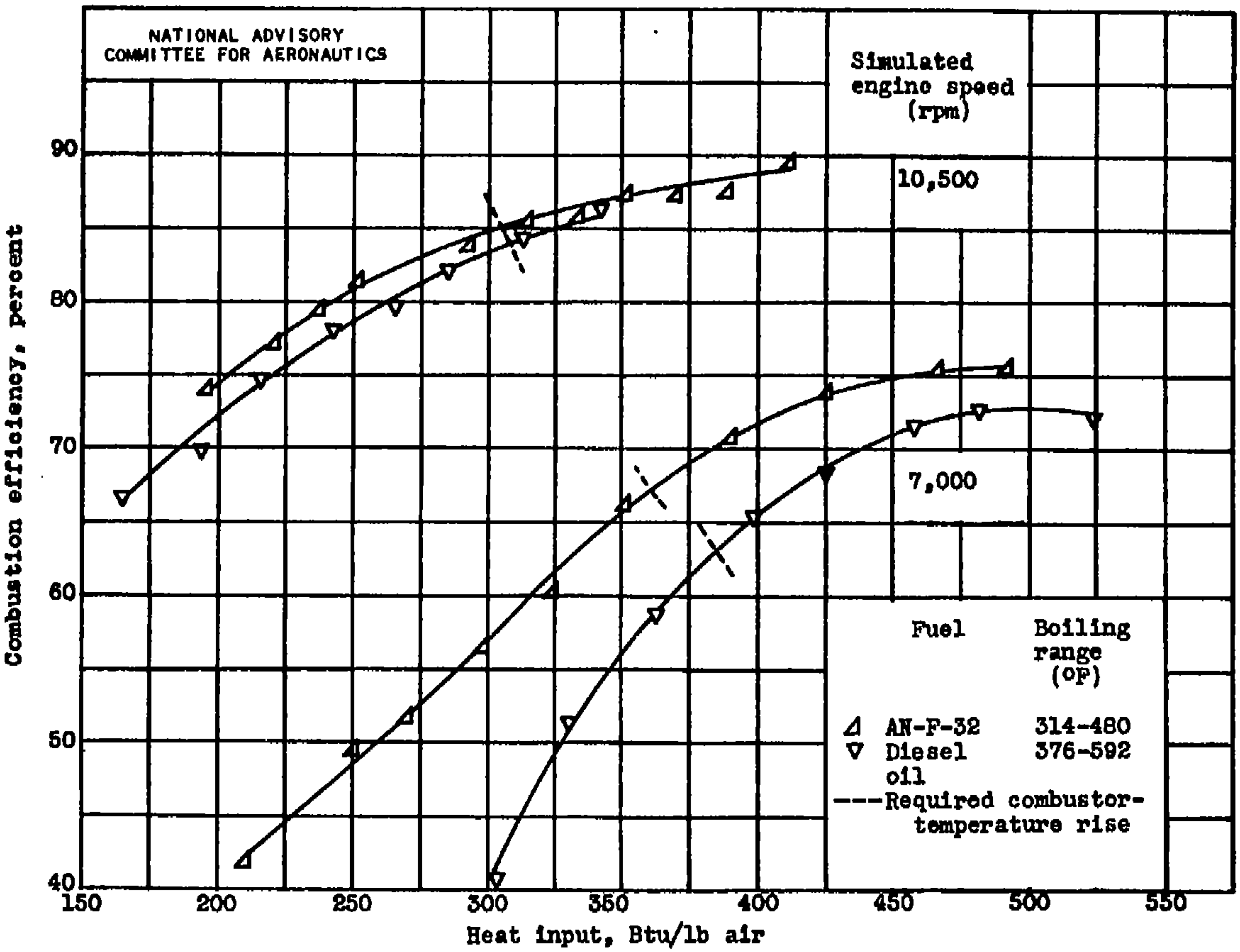
(d) Fuel: Yates 4A

Figure 4. - Continued. Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



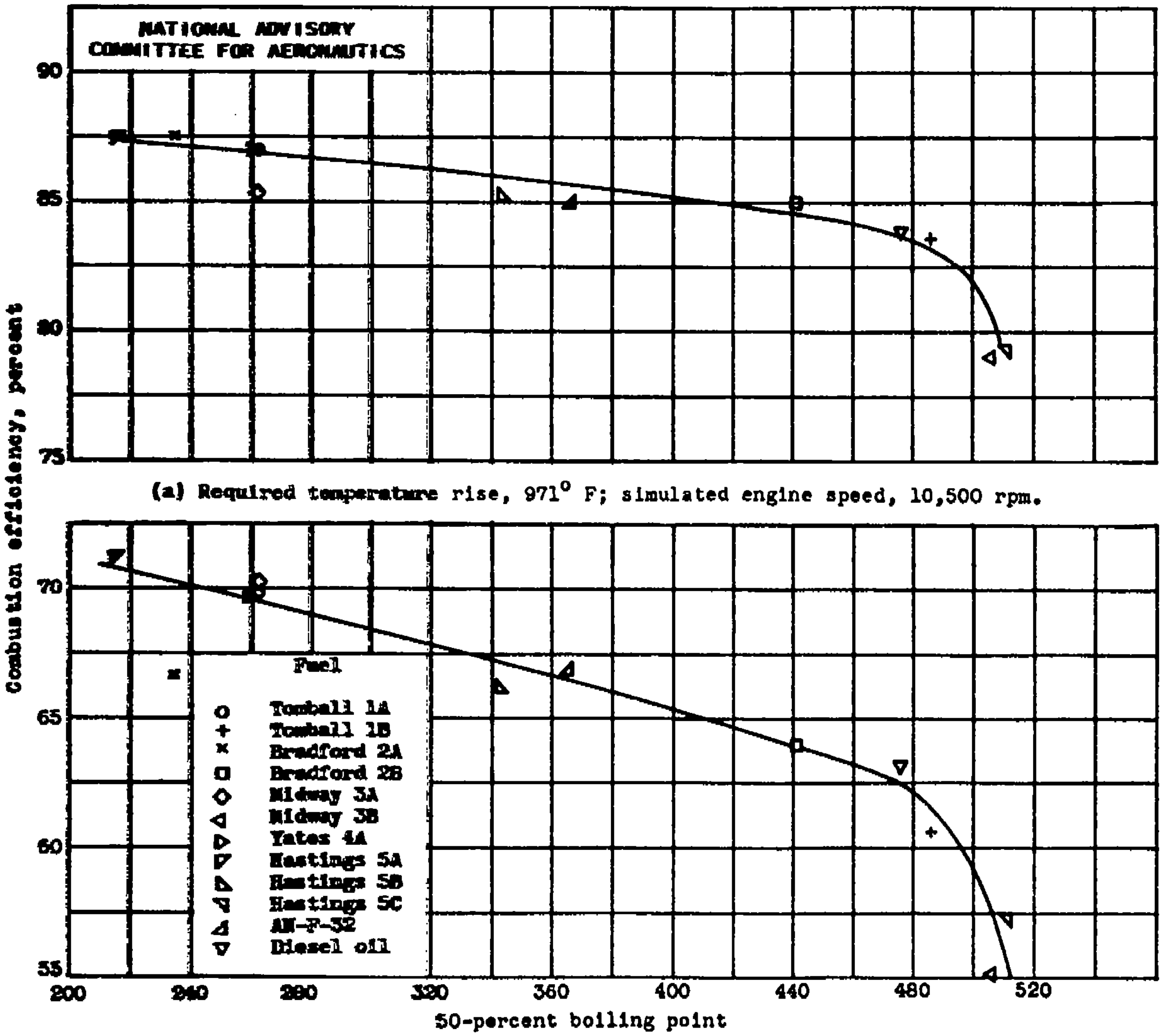
(e) Fuels: Hastings 5A, 5B, and 5C.

Figure 4. - Continued. Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



(f) Fuels: AN-F-32 and Diesel oil.

Figure 4. - Concluded. Variation of combustion efficiency with heat input of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



(a) Required temperature rise, 971° F; simulated engine speed, 10,500 rpm.

(b) Required temperature rise, 892° F; simulated engine speed, 7000 rpm.

Figure 5. - Correlation of combustion efficiency with 50-percent boiling point of various fuels at temperature rise required for turbine operation. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.

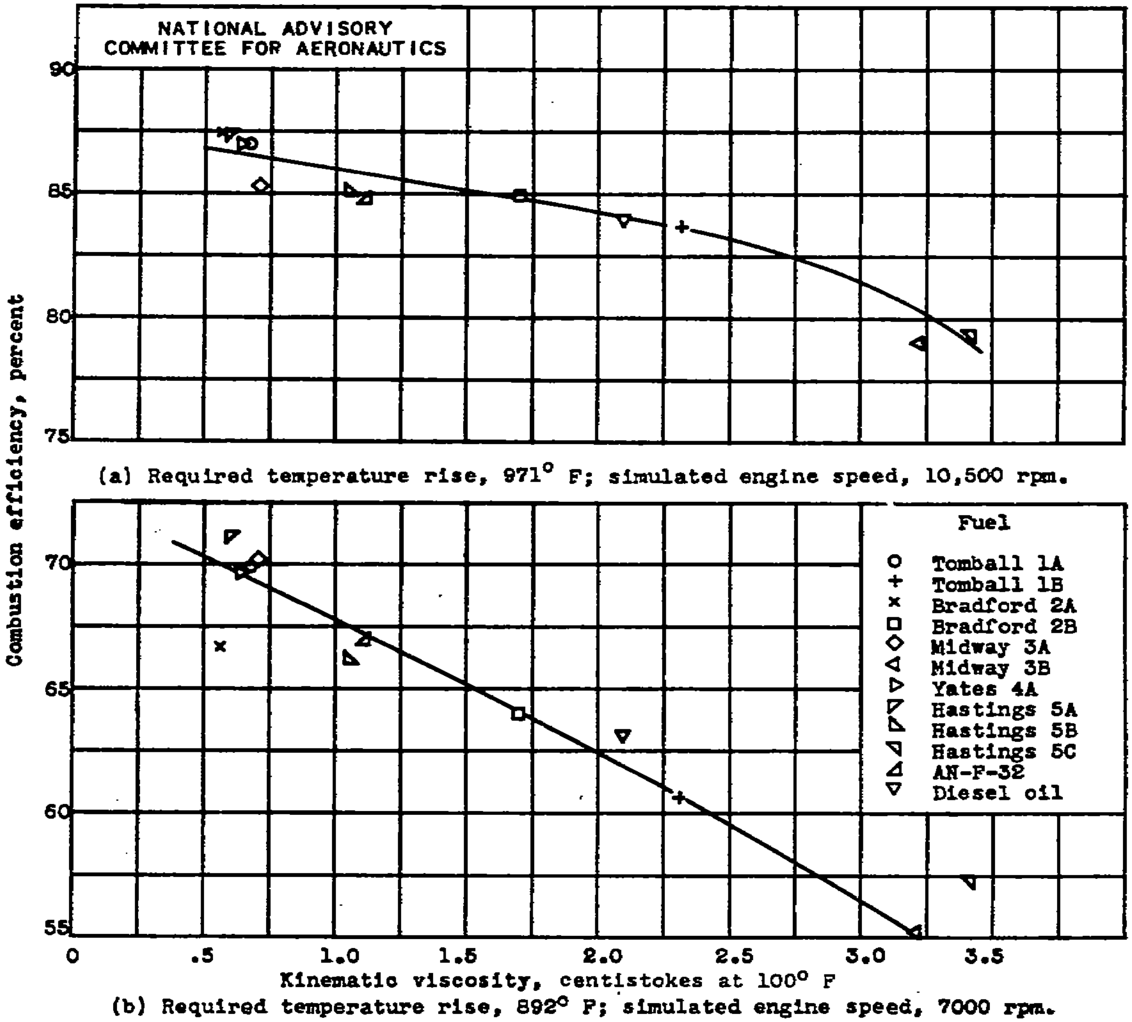
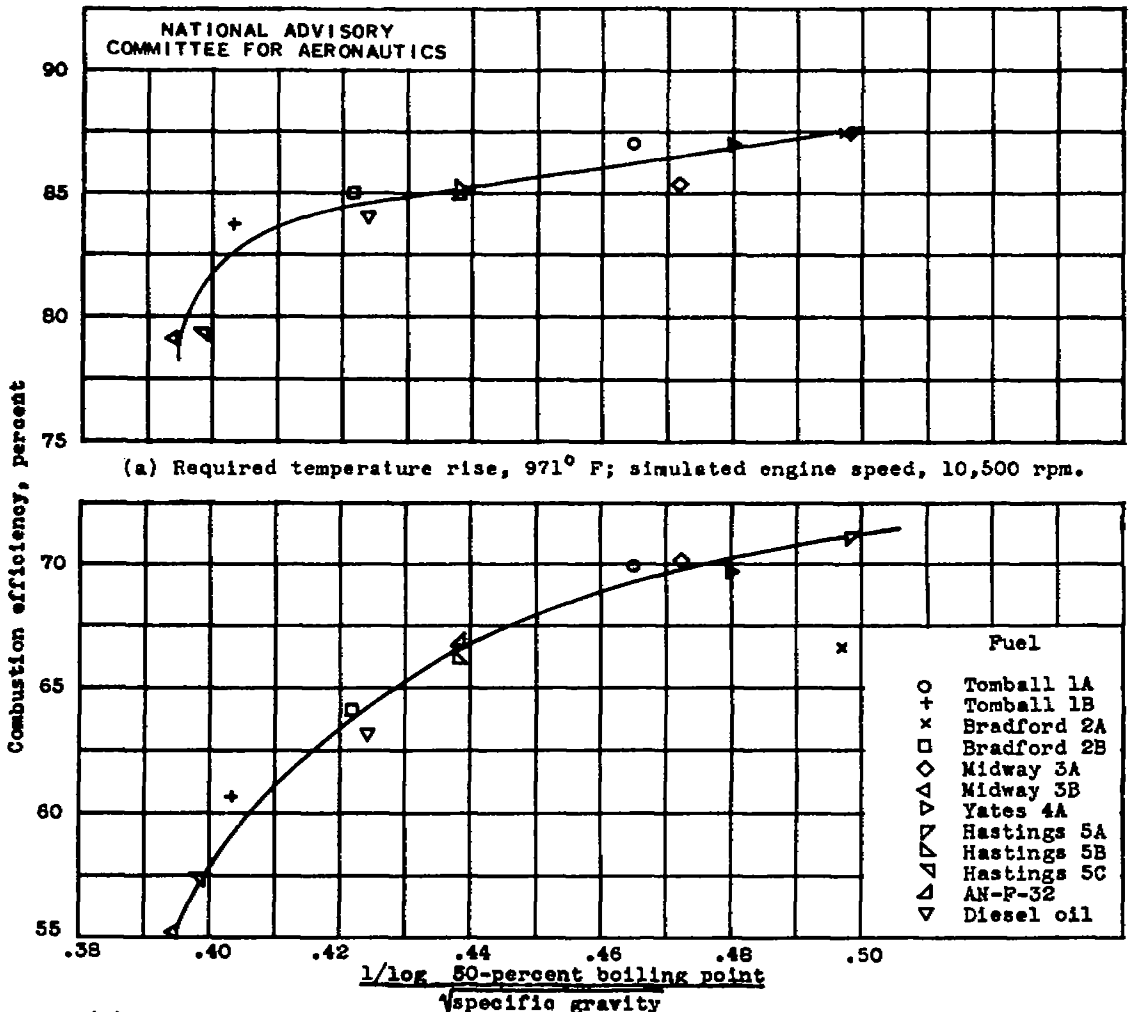


Figure 6. - Correlation of combustion efficiency with viscosity of various fuels at temperature rise required for turbine operation. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.



(a) Required temperature rise, 971° F; simulated engine speed, 10,500 rpm.

(b) Required temperature rise, 892° F; simulated engine speed, 7000 rpm.

Figure 7. - Correlation of combustion efficiency with an empirical function of various fuels at temperature rise required for turbine operation. Conditions simulated engine operation at altitude of 40,000 feet at two engine speeds.

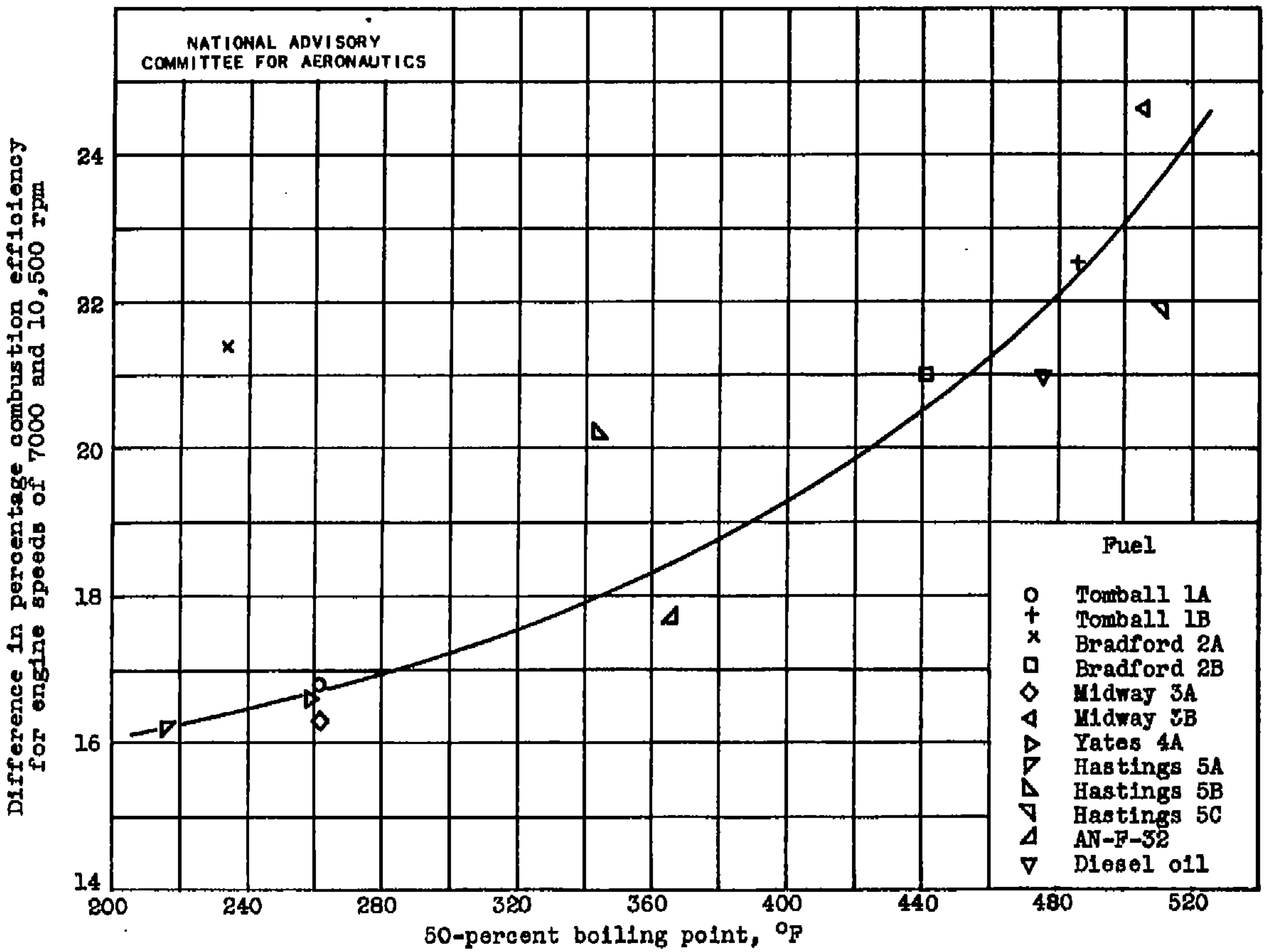


Figure 8. - Variation of difference in percentage combustion efficiency with 50-percent boiling point of various fuels. Conditions simulated engine operation at altitude of 40,000 feet at engine speeds of 7000 and 10,500 rpm.